

Improved Navigation Capability Utilizing Two-Station Tracking Techniques for a Low-Declination Distant Spacecraft

K. H. Rourke and V. J. Ondrasik
Tracking and Orbit Determination Section

The results of an uncompromised accuracy analysis study investigating the advantages of using two-station simultaneous tracking (quasi very long baseline interferometry) techniques to determine the far approach orbit of a distant spacecraft at a low declination angle. The analysis is restricted to batch filtering techniques, but includes the effects of unmodeled spacecraft accelerations. By properly processing the simultaneous doppler and simultaneous range data, the errors resulting from the low-declination geometry are reduced by a factor of two to four, and the errors resulting from unmodeled spacecraft accelerations are reduced by two orders of magnitude.

I. Introduction

Previous *DSN Progress Report* articles (Refs. 1 and 2) have presented preliminary analyses indicating that the use of tracking data taken simultaneously from separate tracking stations provides special advantages in navigating interplanetary spacecraft. Particularly, it is shown that the two-station tracking techniques (sometimes referred to as quasi very long baseline interferometry or QVLBI) promise to be superior to conventional data types in cases when the spacecraft is at a low declination or is subject to unmodelable accelerations. The preliminary analysis results were qualified in the previous articles with the remark that more complete assurance of the value of the QVLBI techniques relies on the completion of (1) more detailed and rigorous orbit determination accuracy analy-

sis studies as well as (2) thorough investigations concerning attainable calibration and measurement system accuracies.

This article addresses item (1) by performing an uncompromised accuracy analysis study of the far approach orbit determination for a *Viking Mission B* spacecraft using analysis analogs of mission operational software. One reason this particular mission was chosen is to illustrate capability of the QVLBI data in alleviating low-declination geometry difficulties.

The simultaneous tracking techniques can be expected to be quite effective in alleviating low-declination and nongravitational acceleration effects for the *Viking Mission*. Indeed, declination errors are shown to be reduced

by factors of two to four while acceleration uncertainty errors are reduced by as much as two orders of magnitude. The accuracy predictions are based on not overly optimistic 3-m ranging accuracies and hydrogen maser frequency standard performance assumptions.

II. Orbit and Data Descriptions

The plane of sky position and velocity of the spacecraft at the beginning and end of the data arc are given in Table 1. Of particular interest is the declination which varies from 11 to 7 deg. Although this is not an extremely low declination, it is low enough to give rise to errors associated with low-declination geometries.

Doppler and range data from DSS 14 (California), DSS 42 (Australia), and DSS 61 (Spain) were taken over a 21-day period according to the tracking pattern shown in Fig. 1.

The study consisted primarily of performing conventional weighted least-squares batch filter solutions, to examine the effects that data noise, station location errors, and process noise have on the estimates of the spacecraft state at epoch. For comparative purposes, parallel solutions were made with the data-taking strategies described in Table 2. These data strategies include: (1) a conventional single-station strategy using nominal accuracy doppler data, with ranging data weighted at 100 m, (2) single-station range and doppler tracking with tight, 3-m range weight specification, (3) single-station doppler with 3-m simultaneous range measurements, and (4) explicitly differenced simultaneous doppler and range data, augmented with loosely weighted conventional range and range-rate measurements. The above-mentioned data weights are data accuracy specifications provided to the orbit determination filter, and should be distinguished from expected measurement precision. For instance, range data of a given quality may be assigned different weights, depending on how well the spacecraft/tracking system environment can be modeled.

III. Effects of Station Location Errors

For orbit solutions using the first three strategies described in Table 2, Fig. 2 shows the formal standard deviations of the declination δ , right ascension α , and their rates $\dot{\delta}$ and $\dot{\alpha}$ produced by data noise only, and errors in the estimate of these same quantities produced by the indicated errors in the station's distance from the Earth's spin axis r_s , longitude λ , and distance from the equator z . The standard deviation and errors of each component are

then root-sum-squared to obtain the consider standard deviation σ_c , which is also shown. The corresponding range, r and range-rate \dot{r}_0 errors are not shown because they are always less than errors in the δ and α directions.

Figure 2 vividly illustrates some of the problems associated with determining the orbit of a spacecraft at low declinations using conventional doppler and range ($\sigma_p = 100$ m) data. Of particular note is the inability to solve for δ and the sensitivity of δ to errors in r_s as shown by the 500-km declination direction error produced by a 1.5-m r_s error. The solution is improved by approximately 30% if the weight on the range data taken at a single station is changed to 3 m.

The dramatic improvement in the solution is provided by the addition of simultaneous 3-m weighted range points from Australia, and may be predicted by the analysis performed in Ref. 1. Specifically, the inclusion of this 3-m QVLBI-type range data reduces the r_s error sensitivity by factors of three or five over the two single-station data sets and increases the ability to solve for δ by a factor of two over the conventional solution. With the inclusion of the QVLBI-type data, the distance of the tracking station from the equator, z_s , becomes an important error source. However, better determination of z_s may be obtained from early QVLBI range data and may then be used in succeeding missions.

As discussed in Ref. 1, there are instrumentation difficulties associated with taking simultaneous range data, and a more realistic procedure would be to take near-simultaneous range data. Solutions were also performed with a data set identical to data set 3 in Table 2, except that the range points were not simultaneous, but separated by 28 min. The results of this solution agreed with the simultaneous range solution to within 5%.

IV. Effects of Unmodeled Spacecraft Accelerations

Although the simultaneous data dramatically reduces the solution errors produced by station location errors, the requirement of tight range weights substantially increases the importance of unmodeled accelerations (process noise) as an error source. These acceleration uncertainties, although often negligible in their direct effect on the actual orbit of a spacecraft, can severely limit the capability of actually solving for the orbit on the basis of conventional tracking data types. As shown in Ref. 2, the tight range weights increase the weight that the orbit determination filter gives to the information supplied by the geocentric acceleration of the spacecraft. However, the

geocentric information is susceptible to process noise effects. In anticipation of the process noise problem, the simultaneous range and range-rate data and the associated partial derivatives may be differenced before processing, thereby allowing separation of the possibly corrupted geocentric components of the data from the still useful topocentric components. Necessary geocentric information (i.e., geocentric range and range rate) can be supplied through suitably weighted conventional tracking data. The details of the differing technique used in this study are described in strategy 4 of Table 2.

The analysis technique used to evaluate the process noise effects is that developed by Curkendall in Ref. 3. The technique enables evaluation of suboptimal, weighted least-squares data filter performance for particular process noise environments. The process noise is modeled with adequate generality as a three-axis exponentially time-correlated stationary Markov process.

Figure 3 presents orbit determination errors due to process noise for the four data sets specified in Table 3. The declination and right ascension direction position and velocity errors are shown for both the process noise errors and a summary of the data noise and station location associated errors already presented in Section III. The process noise magnitude is assumed to be 10^{-12} km/s². The effect of a range of noise correlation times is shown with the bar shading—the lower level corresponding to a relatively optimistic bias noise assumption (infinite correlation time), the upper level corresponding to a pessimistic, rapidly varying noise assumption (5-day correlation time). Although the noise magnitude is given as 10^{-12} km/s², the results are completely general inasmuch as the process noise errors are scalable with respect to the noise magnitude. Of principal interest are the declination position errors shown in Fig. 2a. The conventional data accuracy is relatively insensitive to process noise effects (note the total error effect on the right). This is consistent with past experiences in interplanetary navigation. Strategies 2 and 3, which use precise range information to reduce the station location associated declination errors, are shown to exhibit extreme process noise sensitivities. This effect can be visualized by noting that, although the orbit determination filter expects the spacecraft's geocentric motion to be modeled to significantly better than ± 3 m over two days, the actual spacecraft can be expected to move as much as

$$\frac{1}{2} \cdot 10^{-12} \text{ km/s}^2 (2 \text{ days})^2 \approx 15 \text{ meters}$$

Thus precise range measurements offer significant station

location error reductions, and yet are unreliable because of process noise sensitivity.

Data set 4 includes, in place of the precise simultaneous range (and doppler) measurements, precise *differenced* simultaneous range and doppler measurements. Thus, although some available geocentric information is deleted, the process noise sensitivity should be reduced. The actual results are remarkable. Process noise declination errors are reduced from 1000-km levels to 3 and 2 km for $\tau = \infty$ and $\tau = 5$, respectively. Similar reductions are observed for declination velocity as well as for the right ascension direction errors. Particularly, improvement in process noise sensitivity is not acquired at the expense of a marked increase in other errors. The geocentric range and range-rate accuracies are commensurate with data set 4 conventional data-type accuracies.

V. Process Noise Simulation

To illustrate why solutions made with differenced data are not nearly as sensitive to process noise as those made with conventional data, a simulation study was performed using data residuals produced by the unknown spacecraft accelerations shown in Fig. 4. The station 14 conventional and differenced data residuals are shown in Fig. 5. The most important feature to notice from these figures is that the differenced residuals are two or three orders of magnitude smaller than the conventional residuals. The errors in the batch filter estimate of the spacecraft position and velocity which result from those residuals generated in this way are shown in Fig. 3. As was the case with the residuals, the state errors resulting from the use of differenced data are two or three orders of magnitude less than the state errors resulting from the use of the conventional data.

VI. "Optimal" Processing

A criticism of the analysis in the two preceding sections is that the non-differenced data are treated unfairly, in that an attempt to account for process noise through more modern filtering techniques can be expected to result in significant reductions in process noise sensitivity. "Optimal" processing, by recovering some geocentric information, can be expected to outperform suboptimally processed differenced data, although probably marginally, and at the expense of some sensitivity to the process noise assumptions used in the filter design. If the filter is relatively insensitive to the process noise assumptions, the "optimal" processing techniques will be superior. How-

ever, if the filter is highly sensitive to the process noise assumptions, the explicit differencing technique will obviously be superior. Investigations are currently underway to obtain an idea of how sensitive a representative sequential filter may be to the assumptions regarding the process noise.

VII. Summary and Conclusions

The results of an uncompromised accuracy analysis study have shown that, for the *Viking* Mission under consideration, three-meter simultaneous or near-simultaneous range data are extremely useful in reducing errors pro-

duced by low-declination geometries. However, the requirement of tight range weights substantially increases the sensitivity of the spacecraft state estimate to unknown spacecraft accelerations. It was also shown that this process noise sensitivity can be almost entirely eliminated by explicitly differencing the data taken simultaneously from widely separated stations. Another possible way to circumvent problems associated with process noise is by using sequential filters. This is only a viable alternative if it can be shown that the filter will be insensitive to the process noise assumptions. Investigations are currently under way to obtain an idea of the process noise sensitivity of a representative sequential filter.

References

1. Rourke, K. H., and Ondrasik, V. J., "Application of Differenced Tracking Data Types to the Zero Declination and Process Noise Problems," in *The Deep Space Network Progress Report*, Technical Report 32-1526, Vol. IV, pp. 49-60. Jet Propulsion Laboratory, Pasadena, Calif., Aug. 15, 1971.
2. Ondrasik, V. J., and Rourke, K. H., "An Analytical Study of the Advantages Which Differenced Tracking Data May Offer for Ameliorating the Effects of Unknown Spacecraft Accelerations," in *The Deep Space Network Progress Report*, Technical Report 32-1526, Vol. IV, pp. 61-70. Jet Propulsion Laboratory, Pasadena, Calif., Aug. 15, 1971.
3. Curkendall, D. W., *Problems in Estimation Theory With Applications to Orbit Determination*, Doctorial Dissertation, University of California, Los Angeles, 1971.

Table 1. Description of Viking Mission B trajectory

Coordinate	Value at encounter ^a — 30 days	Value at encounter ^a — 9 days
r , km	0.3300×10^9	0.3489×10^9
δ , deg	11.44	6.853
α , deg	153.8	165.8
\dot{r} , km/s	0.1142×10^{-2}	0.8390×10^{-2}
$\dot{\delta}$, rad/s	-0.3952×10^{-7}	-0.4441×10^{-7}
$\dot{\alpha}$, rad/s	0.1109×10^{-6}	0.1112×10^{-6}

^aEncounter = 23:45:00, August 6, 1976.

Table 2. Data strategies

Data set	Description	Data weights and contributing stations							
		Range		Doppler		Differenced range		Differenced doppler	
		Station	Weight, m	Station	Weight, mm/s	Station	Weight, m	Station	Weight, mm/s
1	Conventional (loose range)	14	100	14	1				
2	Conventional (tight range)	14	3	14	1				
3	Simultaneous range	14, 42	3	14	1				
4	QVLBI	14	10000	42 ^a	100	14, 42	3	14, 42, 62	1

^aOne point per pass.

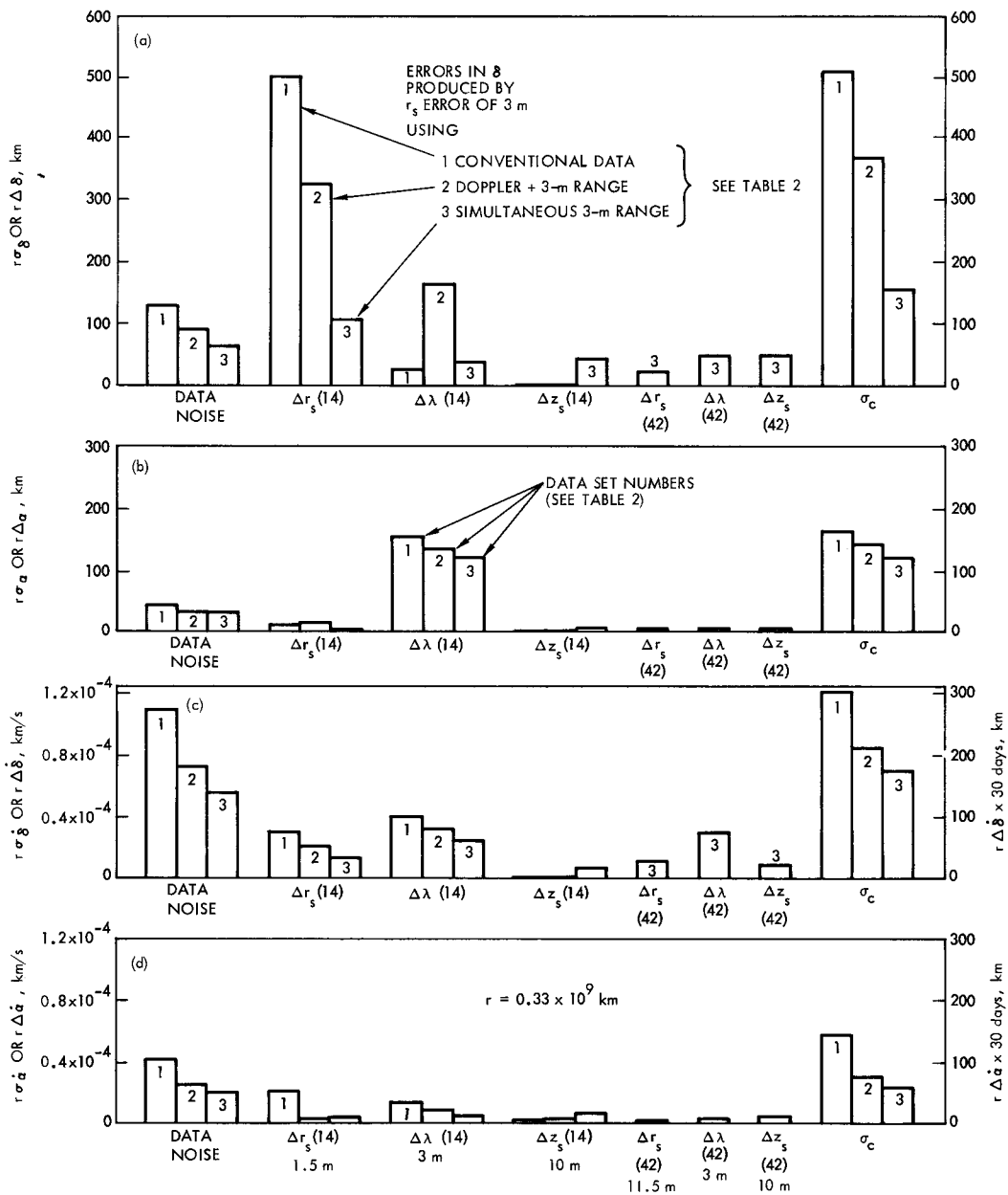


Fig. 2. Errors in δ , α , $\dot{\delta}$, and $\dot{\alpha}$ produced by data noise and station location errors

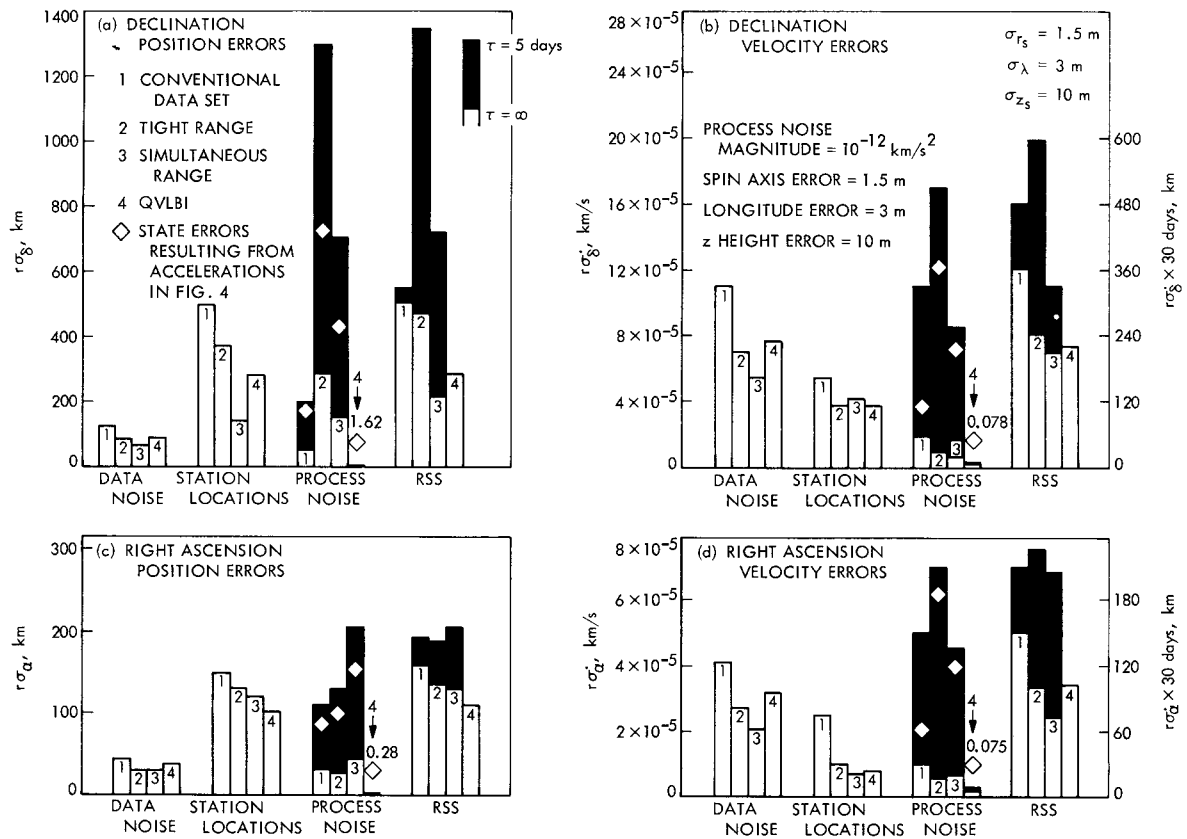


Fig. 3. Position and velocity errors resulting from the use of conventional, simultaneous range, and QVLBI data

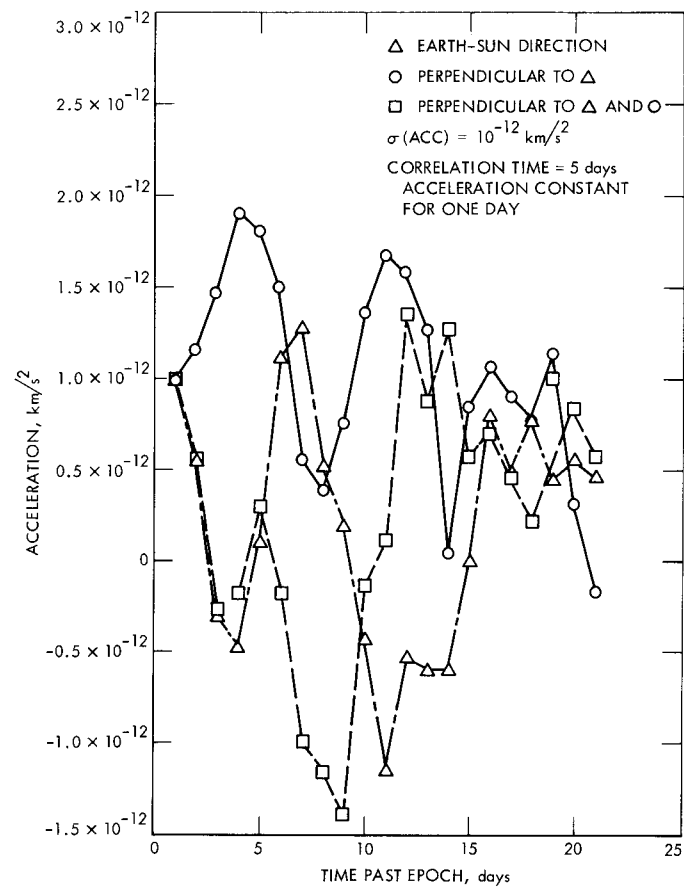


Fig. 4. Simulation accelerations

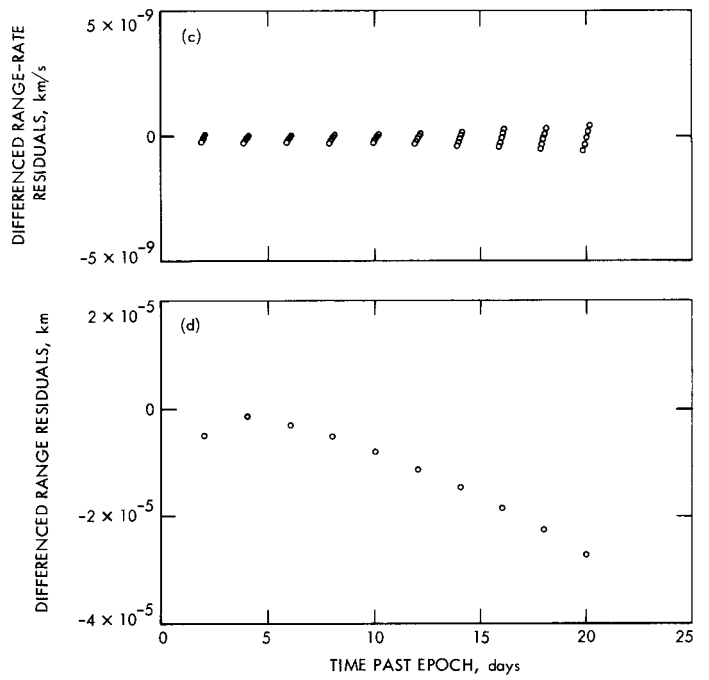
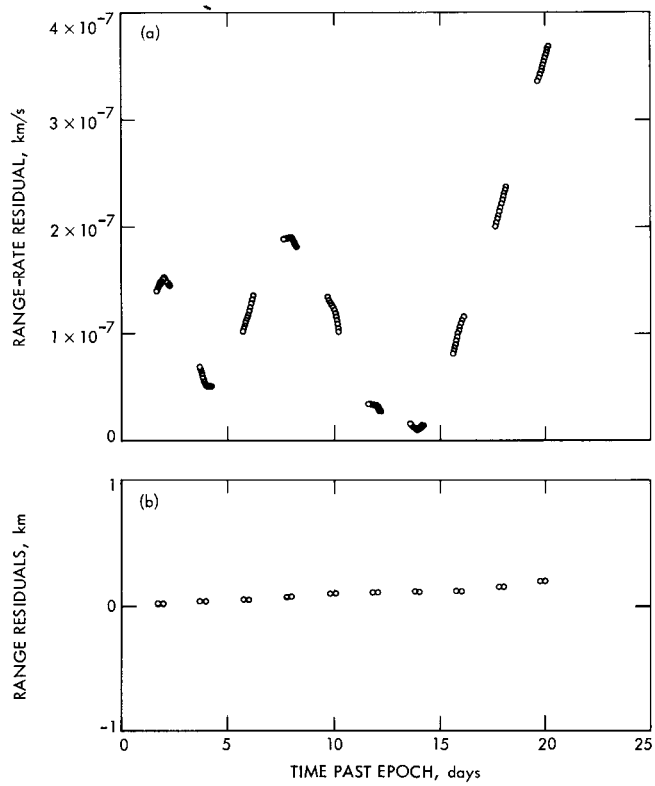


Fig. 5. Conventional and differenced data residuals